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**Large Scale Type II Quantum Computing
In NV-Diamond Using PBG-Based Cavities**

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Objective: The objective of this project is to investigate the feasibility of realizing a large-scale, Type-II quantum computer using NV-Diamond. The resulting device will then be used to demonstrate Type-II quantum computing on many quantum computers (upto 10^4) on the same substrate, each consisting of as many as 10^5 coupled qubits. Furthermore, we will also demonstrate the adiabatic quantum computing for efficient solution of optimization problems that are exponentially difficult.

Approach: In our model, the qubits are spins of color centers in NV-Diamond. The qubits will be located in a single, diffraction limited spot, and will be distinguished from one another via spectral signatures. The inter-qubit coupling will be mediated via a combination of external lasers and single-photons in photonic-band-gap based cavities. The cavities will be etched directly, using lithographic techniques, on to the diamond substrate. The qubits in each spot will represent an individual quantum computer. Many such quantum computers will be realized simultaneously on a single substrate. The resulting Type II QC could be used to implement efficient algorithms for CFD, as well as for adiabatic quantum computing (AQC) for solving exponentially difficult optimization problems. The AQC algorithm models the solution of a search problem as finding the ground state of a set of coupled spins.

Accomplishments: Experimentally, our key accomplishment to date has been the demonstration of alignment of spins (i.e., the individual qubits) in NV-Diamond. Essentially, this represents our ability to initialize all the qubits into their individual (i.e., uncoupled) true ground states, as well as the ability to perform single qubit operations on a collective scale. Furthermore, we have derived the explicit quantum circuits and algorithms necessary for performing the multi-qubit operations, necessary for realizing a quantum computer. These circuit require the realization of low-loss, small volume, high-Q cavities. We have used FDTD codes to design such a cavity --- in two dimensions --- for NV-Diamond. We have also incorporated the cavity-QED equations describing the interplay between optically active color centers and a single photon, in order to optimize the key performance parameter: the number of QC operations that can be performed before decoherence.

Challenges Encountered: In realizing such a cavity, technical challenges have been substantial, given the difficulties in dealing with NV-Diamond. Specifically, there are two different approaches one can follow: (i) create a PBG structure in diamond, then irradiate it with 1 MeV electrons to produce the NV color centers in it, and (ii) irradiate the sample first, then create the PBG structure. Given the complex set of steps of lithography and etching required, it was not clear apriori as to which approach would work better. We have undergone an exhaustive search and consultation with lithography experts, as well as trained one of the post-docs in many of the facilities available to us at

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NWU. Our decision has been to perform the lithography on diamond already irradiated. To this end, we have obtained a 3 μm thin layer of diamond on a 6 inch diameter silicon wafer, and have it irradiate to produce NV centers. We expect to realize a PBG cavity in this substrate shortly.

Relevance to Type II Quantum Computing: In our system, the coupled qubits in each spot together will represent an individual quantum computer. Each spot is potentially very small in volume: 5 μm X 5 μm X 5 μm , for example. In a macroscopic crystal, it should be possible to realize many such quantum computers simultaneously. As such, this system is ideally suited for Type II quantum computing.

Plan Beyond FY03: The current project at NWU is a little more than six months old. As such, the proposal that was submitted for this project already contains information about (a) level of funding requested beyond FY03, and (b) tasks to be performed beyond FY03. Nonetheless, here is a brief summary. The funding level for this project is roughly \$100K per year (with some inflation adjustment every year). The key tasks remaining to be performed beyond FY03 are likely to be as follows:

- *Demonstrate a Control-NOT operation between two qubits.*
- *Demonstrate multi-qubits operation by tuning a cavity.*
- *Demonstrate Type II quantum computing by operating several QC's on the same substrate in parallel.*
- *Demonstrate Adiabatic Quantum Computation for a model search problem.*